Development of CCSDS Proximity-1 Protocol for ISRO's Extraterrestrial Missions

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***Abstract*—Proximity-1 protocol has been the key in successful communication link establishment for a number of extraterrestrial missions. In recent years ISRO has flown missions to the moon and Mars. Given the reliability of Proximity-1 protocol over short distances, it was decided to develop the protocol for ISRO's future space missions where a short haul communication link is required for communication between Rovers, Landers and Orbiters. In this paper we discuss the implementation of Proximity-1 protocol with reference to the requirement of Indian spacecrafts. The paper discusses the modifications and customization made during implementation of the protocol under the purview of protocol standard. Requirements and feasibility of new features such as proximity safe mode and data interface unit are discussed with possible scenarios which may employ them. The safe mode allows usage of all proximity features, but with a greater protocol control and reduced complexity. Data interface unit allows proximity to function as independent module and communicate with higher layers via high speed interfaces. The paper details the response to directives and generation of notifications at various sublayers of the protocol. The protocol is developed and tested on an FPGA platform. Test setup and testing strategies used to evaluate the performance of the protocol at baseband level are also discussed.**

***Index Terms* -** CCSDS, Proximity-1, Protocol, Space link, Data service, sequence controlled, hailing, data link layer

I. Introduction

Proximity-1 protocol standard, given by Consultative Committee for Space Data Systems(CCSDS) provides a link standard for short-range, bi-directional, fixed or mobile radio links, generally used to communicate among probes, Landers, Rovers, orbiting constellations, and orbiting relays [1]. The protocol was conceived during a brainstorming meeting at JPL in 1998 where the experts wanted a protocol which can maximize data collection and improve the reliability of the link to guarantee delivery of data without any errors for NASA's Mars missions [4]. The protocol was based upon the CCSDS Telecommand protocol [5] with addition to a go-back N feature and auto repeat queueing(ARQ) to increase the throughput compared to simpler stop and wait protocols. CCSDS released the first version of Proximity-1 protocol in form of a blue book on October 2002 and since then there had been 4 revisions of the protocol with the latest one released on December 2013. Since its release majority of Mars bound missions have successfully implemented and used Proximity-1 protocol to relay data from rovers/Landers.

Proximity-1 is a link based communication protocol in which a session between the two terminals should be established before the data communication can be initiated. The process of session establishment is known as hailing. The protocol employs a layer based approach like IP but with lot more interaction and control of layers by the application/user via Medium Access Control (MAC) sublayer to increase the reliability. The protocol's rate change feature allows the user to configure the protocol according to the link margin by dynamically changing the communication rate during the session. The protocol provides the user with a reliable and a non reliable but fast data service. The auto repeat queuing (ARQ) with a go-back-N feature of the reliable service (known as sequence controlled service) retransmits the frames in auto mode till their delivery acknowledgement is received hence increasing the reliability as well as throughput of the data service.

The protocol supports communication in broadcast and point to point communication with option for simplex, half duplex and full duplex mode. CCSDS have issued three standard dealing with data link layer [1], coding and synchronization sublayer (part of data link layer) [2] and physical layer [3] of the protocol. In this paper our implementation of data link layer is focused on point to point communication in full duplex mode. A typical application for such configuration is communication between an orbiter and a rover. Implementation focus is on customization of the protocol within the scope of the CCSDS standard to ensure the implementation benefits as well as cross-agency interoperability. Apart from customization, new features are included in the protocol implementation. To allow protocol to interface with users using high speed serial interfaces, a Data Interface Unit (DIU) has been proposed. DIU can support multiple communication standards that can be selected upon need, providing the protocol a more modular approach. Introduction of a Proximity- safe mode allows user/Vehicle controller to take on the full control of the protocol in case of a link contingency. The feature enables the vehicle controller to use all the proximity modules as required.

The rest of the paper is divided into 5 sections. Section 2 will briefly review the protocol standard and outline the customizable areas identified by the authors. Section 3 focuses on FPGA implementation of the protocol and discuss the variation/customizations made within the protocol standard's domain. Section 4 will introduce the new features proposed for the protocol. Section 5 will describe the testing procedure used while the paper concludes in section 6.

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II. Proximity-1 review

This section reviews Proximity-1 protocol's data link layer, highlighting the areas in the protocol that can be tuned according to the implementation requirement. The section only provides cursory review and it is advised to refer CCSDS document on proximity-1 Data link layer [1]. Function of each sublayer is explained followed by the customization fields identified within the sublayer.

CCSDS divides data link layer of Proximity-1 protocol into five sublayers according to their functionality. Figure (1) shows the structure of these sublayers as defined in the protocol standard [1]. The first layer in proximity-1 data flow is Input/Output sublayer. This sublayer is responsible for reception of data from the user. In this paper user is referred to any application that employs proximity-1 to send and receive data. The implementation focus is on deciding the data interface with the user, customizing control signals such as Quality of Service(QOS), Port ID, flow control etc. and formatting frame by aggregating parameters in the 5 byte proximity header.

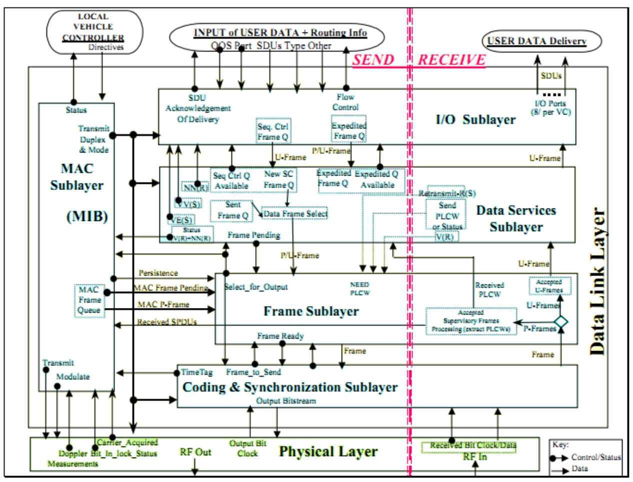

Fig. 1. CCSDS standard Proximity-1 Data link layer

Next in data flow is data services sublayer. Proximity-1 supports two data services viz. sequence controlled and expedited service, providing a reliable and an unreliable but simpler data service to user respectively. Data services sublayer is responsible for managing these data services. Implementation focus include managing frame storage for either services, maintaining the Communication operation procedure (COP) State variables [1], generation and reception of Proximity link control word (PLCW), taking action on clear queue directive, deciding on when to raise resync flag, reaching the optimum queue length, managing/implementing queue mechanism and retransmission logic. List of state variables referred in this paper is presented in table I. The implementation should also decide whether to provide all these features in Data services sublayer or relegate them to other sublayers.

Further in the data flow is frame sublayer, whose major responsibility is implementation of priority logic for selection of frame. This logic is very well defined by the CCSDS document. Still the implementation grey areas include generation of PLCW and status reports and relaying data to lower sublayers.

TABLE I
Proximity state variables

	Variable	Description
1.	V(E)	Sequence number of next Expedited frame to be sent.
2.	V(S)	Sequence number of the next new Sequence Controlled frame to be sent.
3.	VV(s)	Sequence number to be assigned to the next Sequence Controlled frame to be sent.
4.	N(R)	Copy of the Report Value from the current PLCW.
5.	NN(R)	Copy of the Report Value from the previous valid PLCW.
6.	V(R)	Sequence number plus one of the last Sequence Controlled frame acknowledged by the receiver
7.	N(S)	Sequence number contained in the transfer frame header of the received Proximity-1 Frame

The last sublayer in data flow structure in Proximity-1 protocol's data link layer is coding and synchronisation sublayer. True to its name, the major task of the sublayer is providing platform for synchronization and coding/decoding of frames. The sublayer has only a few fill-ups for implementation in the form of providing output clock, generating notification upon radiation of frame and time tags. Since the focus of this paper is data service implementation, timetags will not be discussed.

Medium Access Control (MAC) sublayer is not the part of data flow, but nonetheless produces supervisory frames (SPDU) which are transported to the remote terminal via proximity-1 channel. The sublayer generates control signals responsible for session establishment, control/communication parameter change, resynchronization, link upkeep and session termination . Implementation issues include resynchronization process, local and remote directive decoders and deciding interface with local vehicle controller. Deciding mode of operation(duplex, simplex etc.)and communication parameters are management decisions taken based on user requirements.

The receive functionality of the four layers involved in data flow as shown in figure (1) is limited compared to their send functionality. Therefore for implementation all these functionalities are clubbed into one module referred as receive unit. The implementation issue remains deciding what functionalities should be combined, distribution of frames to various layers and user frame port management.

Data interface unit (DIU) shown in figure (2) is not the part of protocol standard and hence is not shown in figure(1). The purpose of this module is to provide selectable interfaces between proximity and the user. DIU increases the modularity and ease of implementation for the protocol as the required interface can be selected from DIU. Another new feature of proximity safe mode is also presented in implementation. This feature do not require a separate unit and is only an addition to the standard.

III. Protocol implementation

A. I/O Sublayer

I/O sublayer receives serial data, clock and a data qualifier window line from the user. User also provides I/O layer

with QOS signal to decide the quality of service and Output port ID as these parameters can change dynamically. Other inputs such as Remote Spacecraft ID, Source or destination identifier are provided by MAC sublayer and are changed by issuing local directives. The segregation of input parameters for frame header formation is done on based of relative static and dynamic nature of the parameters and to avoid multiple interface of vehicle controller with proximity-1 unit. The I/O sublayer provides user with two flow control signals one for each of the two data services. This allows user to employ expedited data service if sequence controlled queue is full and vice versa.

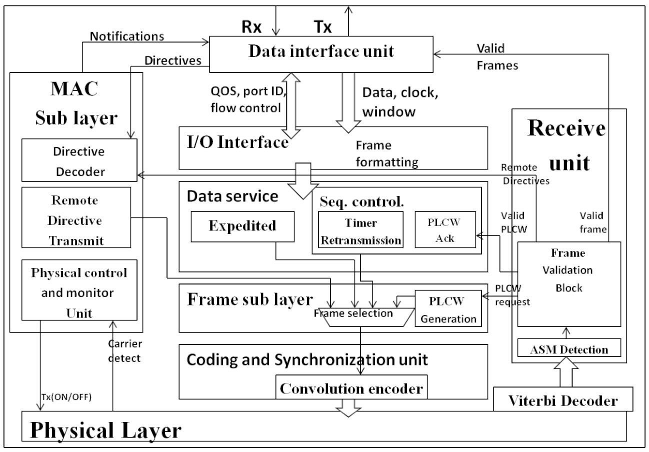

Fig. 2. Proximity-1 Data link layer implementation

The user is not expected to generate a supervisory protocol data unit (SPDU) and hence PDU type is not taken as input from the user. Instead SPDUs are generated by MAC layer and generation of all the SPDUs are controlled by local directives. In our application, the controlling body and intelligence sits entirely with local vehicle controller which interacts with MAC layer as shown in figure (1). Hence notification of frame generation and delivery are not generated by I/O sublayer. Instead all the notifications are generated by MAC sublayer and are transferred to local vehicle controller for processing and decision making.In our implementation I/O sublayer maintains the frame sequence variable V(S) and frame header is also formed and stored in memory along with the user data at I/O sublayer. This task reduces the complexity of reforming header during retransmission.

The state diagram shown in figure (3) shows the three basic states in functionality of I/O sublayer. I/O sublayer maintains two such state machines for independently servicing data frames with different quality of service. Data is transferred to Data services sublayer if the sublayer is ready to receive the frame of particular data service.

B. Data Service Sublayer

Data services sublayer(DSS) contains two modules, each dedicated to either of the data services. User data along with frame header is received and stored in a memory queue by

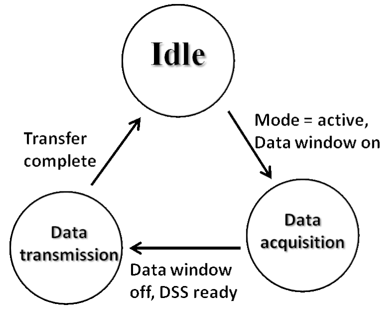

Fig. 3. state transition diagram for I/O sublayer

the Data Services sublayer. The queue length for sequence controlled service is calculated based on maximum number of back to back frames that can be sent out before a valid PLCW is expected. For this calculation, following parameters are assumed.

Distance : D (max).

Frame Size : 2048 bytes(max).

Data rate : Rd kbps (max).

From these specifications, one way time (OWT) for the frame maybe calculated as

$$OWT = D/C. \tag{1}$$

Where C is speed of light in vacuum.

For worst case calculation, lets assume that when a frame arrives at reception node of proximity, it has already begun transmission of its own frame. Therefore till transmission of the frame is not completed, PLCW cannot be transmitted. The transmission delay (Td) will be given by

$$Td = 2048 * 8/Rd. \tag{2}$$

Adding this delay to the total time, we get total delay(T_{Delay}) as

$$T_{Delay} = 2OWT + Td \tag{3}$$

Finally, dividing total delay by transmission time and rounding it off to next higher integer gives us queue length(Qu).

$$Qu = T_{Delay}/Td \tag{4}$$

For example if we select maximum range supported by proximity (100,000 km) and bit rate as 64 Kbps we obtain optimum value of ‘Qu’ as 4.

Expedited service module in Data services sublayer perform a simple function of accepting frame from I/O sublayer and forwarding it to Coding and synchronization sublayer(CSS) based on signal from frame sublayer. Sequence controlled service module on the other hand involves more complex operation of implementing FOP (Frame operations Procedure)

and FARM (Frame Acceptance and Reporting Mechanism) operations [1].

Frame received from I/O layers is stored in memory and transmitted to CSS before another frame is accepted. As shown in state diagram of figure (4), default state is selection state. First priority is given to a retransmission request received via PLCW. Second priority is assigned to acceptance and transmission of new frame. Last priority is given to initiate a progressive retransmission. Once retransmission flag is high, all the unacknowledged frames in the queue are retransmitted. Variable 'num_of_frames' contains difference of V(S) and N(R) and will indicate how many frames are to be transmitted. When in transmission state, this variable is reduced by one each time a frame is transmitted. When 'num_of_frames' becomes zero, state is changed to selection again. Two modulo 'Qu' memory pointers are used to make the usage of memory queue cyclic. These pointers are M_old and M_next which point to the oldest unacknowledged and the next memory location for frame storage respectively.

For FARM operation, the PLCW is received from 'Receive Unit' and is validated according to standard. The frames are acknowledged by incrementing M_old, N(R)-NN(R) times. PLCW generation being simple operation is implemented in frame sublayer. Whenever a valid PLCW arrives, MAC sublayer is signalled to generate a notification to Vehicle controller giving information about the frame successfully delivered.

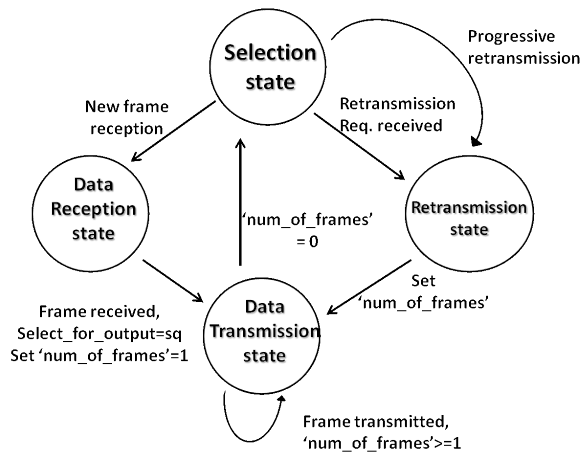

Fig. 4. Sequence controlled logic.

For resync operation, resync timer is present in the DSS which expires if no PLCW is received within a particular duration which is an integer multiple of 'PLCW_Repeat_Interval'. These intervals are calculated proportional to the expected FER (Frame Error Rate) for the desired link environment. If DSS contains no unacknowledged frames, resync timer is disabled. If MAC sublayer's resync process fails, a clear queue directive is issued Clear queue directive makes M_next equal to M_old and V(S) is made equal to NN(R)+1 value.

C. Frame Sublayer

Frame sublayer employs a priority logic to select between SPDU from MAC sublayer, expedited and sequence controlled frames generated at DSS and PLCW/Status report. PLCW is generated within frame sublayer on cue from the Receive Unit. PLCW repeat timer which enables generation of PLCW at regular interval is also implemented with the frame sublayer. Status reports are also generated within Frame sublayer and are treated as SPDUs.

D. Coding and Synchronization Sublayer

Coding and synchronization sublayer(CSS) collects data from different sublayers via Frame sublayer and calculates 32 bit cyclic redundancy check(CRC) [2] . After prefixing the frame with an attached synchronous marker(ASM) the frame and CRC is coded and radiated. Frame radiated signal is generated by CSS and given to MAC sublayer for formation of a notification to the user. This notification is useful when using expedited service as there is no delivery notification for expedited service..

E. Receive Unit

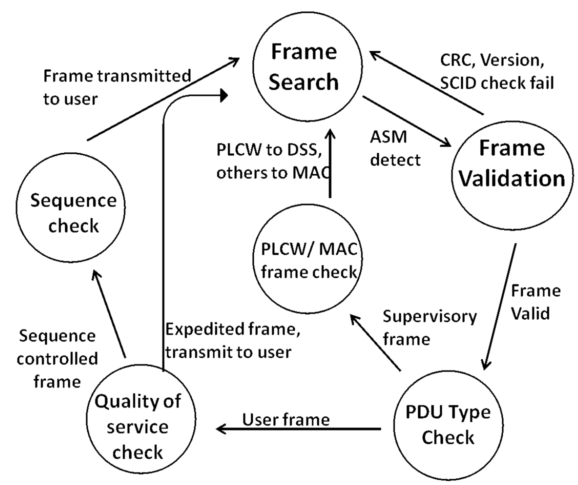

Fig. 5. Receive Module state diagram.

For ease of implementation, the receive functionality of all the sublayers as shown in figure (1) is implemented in the Receive Unit. The unit receives data from a decoder (Viterbi decoder). The default state of the unit's state machine shown in figure (5) is frame search state. In this state, the receive unit searches for ASM. Given the possibility of phase inversion in BPSK, both ASM and its bit inverse are searched. If the inverse of ASM is detected, all the subsequent bits are inverted. This method allows solving phase inversion without use of differential encoding. Upon detection of ASM, the frame is inspected for Spacecraft ID, Version number and CRC related errors. Valid frames are segregated into SPDUs and user frame. SPDUs are further checked if they are PLCW or not. PLCWs are transferred to DSS while other SPDUs are transferred to MAC sublayer. User frames are again checked

for their quality of service. Expedited frames are transferred to user without any further checks through appropriate user port while sequence controlled frames are checked for in-sequence arrival by comparing N(S) with V(R). For a frame to be valid, its N(S) should be equal to V(R) value of the receiver module. If N(S) is less than V(R), it denotes that the received frame is repetition of an already acknowledged frame. This condition can arise if the PLCW for the frame was lost. A fresh PLCW can be issued under this circumstance to avoid unnecessary retransmission of frames under progressive retransmission mechanism. If N(S) is grater than V(R) it denotes a gap in sequence that may arrive due to sequence control frame loss. Under such condition a PLCW is sent with retransmission bit set to high. Valid frames are forwarded to user at requested virtual output port while invalid frames are rejected. In both cases frame sublayer is signalled for generation of PLCW with appropriate setting of retransmission flag.

Combining all these operations in one unit eases up implementation and reduces interlayer connections. Receive unit provides MAC sublayer with notifications about frame error and its type along with V(R) value which is used in 'set V(R)' directive and resync process.

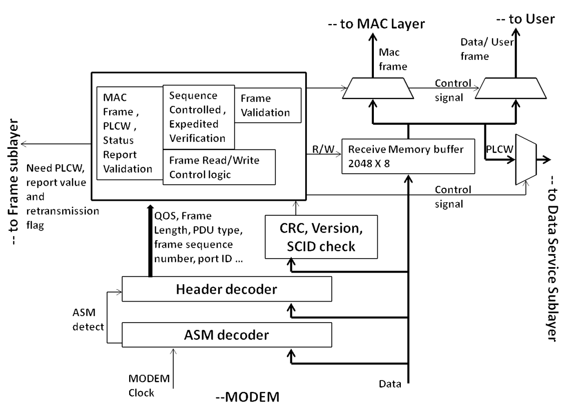

Fig. 6. Receive Module.

F. MAC Sublayer

MAC sublayer interfaces all sublayers in data link layer and physical layer with local vehicle controller. Commands are issued to MAC sublayer in form of Local directives which are decoded and executed by local directive decoder as shown in figure (7). Along with the directives mentioned in the standard [1], new directives are also added to change the static parameters such as space craft ID, Source or destination parameter and PDU type. Directives to issue a set V(R) command and ask for status report is also included. Notifications for various events are provided to the local vehicle controller to take necessary action. List of these notifications is provided in table (II) with new notifications marked with a'*' mark. MAC sublayer also issues remote directives which are transmitted to remote proximity terminal in form of SPDUs. A Remote

TABLE II
NOTIFICATIONS

	Notification	Description
1.	Hail success	Report that link is successfully established.
2.	Hail failure	Report that attempt to establish link was unsuccessful.
3*.	Directive rejected	Report the reason why local directive was rejected.
4.	Carrier detect only	Report that carrier only was detected after the Wait for Hail Response state terminated.
5.	Carrier lost	Report that carrier loss timer has expired.
6*.	Configuration change	Report that a control or communication parameter was changed.
7.	Sync timer expired	Report that a valid PLCW is not received in specified duration
8.	Resync failed	Report that attempt to Resync has failed.
9*.	Set V(R) requested	Report either Set V(R) request was generated or received.
10*.	Status report requested	Report when status report generated, requested or received.
11*.	RNMD requested	Report that Remote terminal have no more data to send
12*.	PLTU Radiated	Report when an expedited PLTU was radiated.
13*.	PLTU Delivered	Report when a sequence controlled frame was delivered.
14.	Frame error	Report when a frame arrives with either Space craft ID, version ID or CRC error.
15.	State variable status	Report the State variable status upon request.
16.	Timing services	Report about status and roundtrip time calculation for timing services.
17*.	Session terminated	Reports when a session is terminated.

directive decoder receives, decodes and executes these SPDUs. Apart from directives specified in the standard, new directives for status report and set V(R) are included. Various timers who take their value from Management information base(MIB) are also maintained by MAC sublayer. These timers include Hail wait timer, Carrier only duration, carrier in-lock timer, tail duration and hail attempt lifetime. MAC sublayer also provides static informations such as SCID and source or destination mode to I/O sublayer.

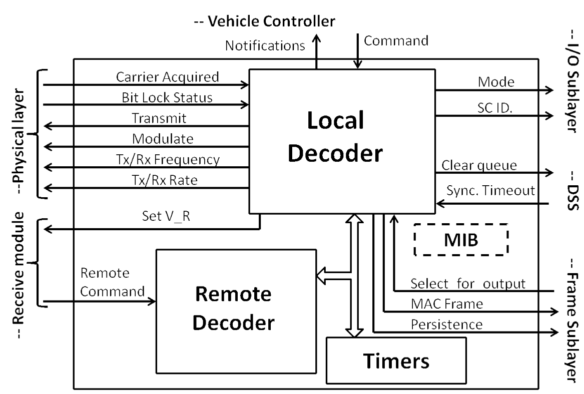

Fig. 7. Medium Access Control Sublayer

MAC sublayer executes task such as establishment of session, termination of session, acquisition of status reports and Resync operations. Resync flag is raised by DSS and in response, MAC layer sets the persistence flag to frame sublayer. During persistence only MAC SPDUs are allowed to be radiated and user frames are not allowed service. MAC sublayer copies NN(R) from DSS and issues set V(R) command. As a response to set V(R) command, MAC sublayer receives a status report. IF the report value of status report, which contains V(R) value of the remote terminal is found equal to NN(R) of local terminal, normal operation is resumed. But if satisfactory report is not received within stipulated time, a clear queue directive is issued to I/O sublayer and DSS which clears all the unacknowledged frames in the queue. Also, a notification is issued to user to take a decision on quality of service for further frames within the given session.

IV. New features

A. Proximity Safe Mode

Proximity Safe mode is a feature that allows usage of proximity modules in a manual mode. Though proximity-1 protocol is highly reliable protocol, but if due to some unforeseen conditions, protocol is not able to establish a session automatically, the hail procedure of link establishment can be bypassed by using the proximity safe mode. Proximity Safe mode allows Local vehicle controller to control all the protocol modules, send and receive remote directives and User data. To enable this feature, the Receive Unit is kept operational in all modes. To bypass hail procedure, Local vehicle controller issues a 'Set mode' local directive to MAC sublayer, which forcefully set the protocol mode to active and allows usage of data service. Further using the data service, commands can be sent to the vehicle controller of remote Proximity unit to issue a similar bypass command to the proximity protocol unit at remote terminal and allow data flow from remote to local terminal. Preferred data service during this operation is expedited although sequence controlled service can also be used. The Safe mode also allows SPDUs to be sent via data path by forcing PDU type identifier issued by the MAC sublayer to the I/O sublayer to one.

The safe mode can be used when the devices other than the proximity module fails to perform. A typical example involves demodulator failing to provide a carrier or symbol lock status. In such case, proximity will not be able to establish the connection automatically. The user can then try sending data/ commands to the remote terminal using proximity safe mode and if a response is received, continue in safe mode. The safe mode also proves useful if the carrier in the link is erratic. In such case, the session will be abruptly terminated each time the carrier in-lock timer expires. The advantage of proximity safe mode is that it does not totally bypasses the protocol but only allows user more control over the protocol modules.

B. Data Interface Unit

Data Interface unit(DIU) is customizable hardware unit that acts as an interface between Proximity protocol unit, the user and local vehicle controller. The unit has relevance at implementation level. Depending on the spacecraft employing proximity protocol, interface of protocol with user can be through different standard interfaces such as serial port RS232, Mil STD 1553 , space wire etc. To make proximity more modular in such case, data interface unit is used. The unit contains selectable interfaces that connects proximity to user and local vehicle controller. The DIU shown in figure (2) performs the function of receiving and sending data from proximity unit and convert it into selected interface's packet format. For testing purpose, DIU implemented in figure (2) contains a RS232 transceiver, local storage unit and a packet decoder. Packet decoder decodes the packet and transfers the frame to proximity in the standard format. Decoder also set the control signals according to the information in the packet. DIU's focus is on providing high speed interface with user and provide data and control signals to proximity unit such that DIU is the only variable unit when design is ported from one spacecraft to other.

V. Testing

To test implementation of Proximity-1 protocol, a test set up shown in figure (8) was used. The test set up contains two proximity nodes implemented on Xilinx Virtex-4 FPGA. Other systems such as user and vehicle controller were simulated using separate PC for each proximity node. Commands and data were communicated to FPGA via a serial interface and were converted to standard interface by the Data Interface Unit as shown in figure (2). The data exchanged between the two nodes was tapped by a monitoring module which receives all the data and store/display the frames on another PC for manual validation. Switches were used on all the data lines to simulate various link disruption contingencies .

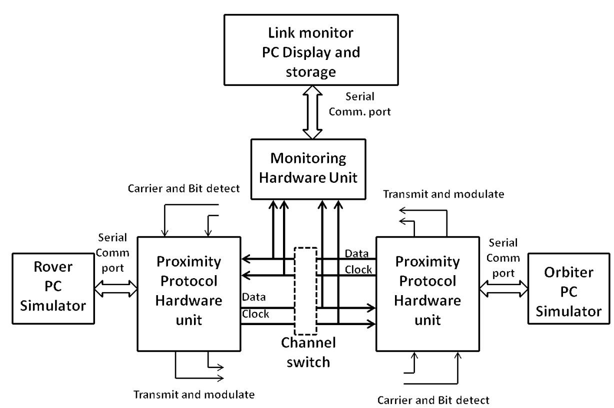

Fig. 8. Test Setup for Proximity-1 Validation

The set up was used to test following features of the protocol.

Hailing and session establishment

Expedited services operations.
Sequence controlled service operations.
Normal termination.
Forced termination.
Verification of directives and notifications.
Verification of priority for frames.
Synch time-out conditions.
CRC errors by manipulating switches
Proximity safe mode operations.

All the tests were carried out for extended duration as well as shorter durations with data transfer carried out over multiple sessions

VI. Conclusion

In this paper, we have reviewed CCSDS proximity-1 protocol. Implementation for different sublayers of the data link layer is discussed and customizations made to standard protocol were highlighted along with their implementation advantages. New features of proximity safe mode and data interface unit were discussed with advantage of using these features clearly justified. The protocol was tested and verified on Xilinx Virtex -4 FX60 and Actel ProASIC AP3E3000 FPGAs according to the test setup described in testing section. All new, modified and standard features of the protocol performed as per expectations. The configuration is targetted for ISRO's future extraterrestrial missions.

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